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14. ABSTRACT Bridge scour dynamics are dominated by the complex interaction between the approach flow, the erodible bed and the foundation itself. Our basic premise is that fluctuating hydrodynamic forces due to the foundation-induced coherent vortices are responsible for the development of scour holes around bridge piers. This premise was tested here through a series of small scale more detailed laboratory experiments that were carried out at Virginia Tech (with rigid bottom and erodible boundary) and near prototype conditions performed at Waterways Experiment					
15. SUBJECT TERMS bridge scour, horseshoe vortex, large Reynolds number experiments					
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## Report Title

Physics-Based Modeling of Bridge Foundation Scour: Numerical Simulations and Experiments

### ABSTRACT

Bridge scour dynamics are dominated by the complex interaction between the approach flow, the erodible bed and the foundation itself. Our basic premise is that fluctuating hydrodynamic forces due to the foundation-induced coherent vortices are responsible for the development of scour holes around bridge piers. This premise was tested here through a series of small scale more detailed laboratory experiments that were carried out at Virginia Tech (with rigid bottom and erodible boundary) and near prototype conditions performed at Waterways Experiment Station (with an erodible boundary). The pier based diameter Reynolds number,  $Re_D$ , for all these experiments ranged from 26000 to nearly 106. A Digital Particle Image Velocimeter was employed to capture the unsteady dynamics of the flow and a new non-intrusive stereo-photogrammetric technique was developed to reconstruct the three-dimensional scour hole temporal evolution. Post-processing analysis of data reveals an intricate dynamic flow structure in the vicinity of the pier whose behavior is affected by  $Re_D$ , scour hole stage and possibly bed porosity. Three separate phases of scour hole development were identified, with the initial one occurring more rapidly over a relatively short duration and accounting for nearly 75% of the total excavation.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

ReceivedPaper

- 03/07/2011 10.00 N. Apsilidis, P. Diplas, C. Dancey, F. Sotiropoulos. The effect of Reynolds number on junction flow dynamics,  
, (03 2011): . doi:
- 03/07/2011 8.00 M. Valyrakis, P. Diplas, C. Dancey. On the impulse criterion for entrainment of coarse grains in air,  
, (01 2010): . doi:
- 03/07/2011 2.00 M. Valyrakis, P. Diplas, C. Dancey, A. Celik. of instantaneous force magnitude and duration on particle entrainment,  
Journal of Geophysical Research, (04 2010): . doi:
- 03/07/2011 3.00 A. Celik, P. Diplas, C. Dancey, M. Valyrakis. Impulse and particle dislodgement under turbulent flow,  
Physics of Fluids, (04 2010): . doi:
- 03/07/2011 4.00 P. Diplas, C. Dancey, A. Celik, M. Valyrakis, K. Greer, T. Akar. The Role of Impulse on the Initiation of Particle Movement Under Turbulent Flow Conditions,  
Science, (10 2008): . doi:
- 03/07/2011 1.00 P. Diplas, A. Celik, C. Dancey, M. Valyrakis. Nonintrusive Method for Detecting Particle Movement Characteristics near Threshold Flow Conditions,  
Journal of Irrigation and Drainage Engineering, (11 2010): . doi:
- 03/07/2011 7.00 A. Celik, P. Diplas, C. Dancey. Instantaneous pressure measurements on a spherical grain under threshold flow conditions,  
, (01 2010): . doi:
- 03/07/2011 6.00 M. Valyrakis, P. Diplas, C. Dancey. Incipient rolling of coarse particles in water flows: a dynamical perspective  
,  
, (09 2010): . doi:
- 03/26/2013 23.00 Ahmet Ozan Celik, Panayiotis Diplas, Clint L. Dancey. Instantaneous turbulent forces and impulse on a rough bed: Implications for initiation of bed material movement,  
Water Resources Research, (03 2013): 0. doi: 10.1002/wrcr.20210
- 03/26/2013 26.00 Polydefkis Pol Bouratsis, Panayiotis Diplas, Clinton L. Dancey, Nikolaos Apsilidis. High-resolution 3-D monitoring of evolving sediment beds,  
Water Resources Research, (02 2013): 0. doi: 10.1002/wrcr.20110
- 07/21/2012 15.00 Manousos Valyrakis, Panayiotis Diplas, Clint L. Dancey. Entrainment of coarse grains in turbulent flows: An extreme value theory approach,  
Water Resources Research, (09 2011): 0. doi: 10.1029/2010WR010236
- 07/21/2012 16.00 Manousos Valyrakis, Panayiotis Diplas, Clint L. Dancey. Prediction of coarse particle movement with adaptive neuro-fuzzy inference systems,  
Hydrological Processes, (10 2011): 0. doi: 10.1002/hyp.8228

**TOTAL: 12**

Number of Papers published in peer-reviewed journals:

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(b) Papers published in non-peer-reviewed journals (N/A for none)

Received                  Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

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(c) Presentations

Number of Presentations:        0.00

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received                  Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
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03/26/2013	24.00	N. Apsilidis, A. Khosronejad, F. Sotiropoulos, C.L. Dancey, P. Diplas. Physical and Numerical Modeling of the Turbulent Flow Field Upstream of a Bridge Pier, ICSE6 Paris. 2012/08/27 00:00:00, . : ,
07/21/2012	18.00	Nikolaos Apsilidis, Ali Khosronejad, Panayiotis Diplas, Fotis Sotiropoulos, Clint Dancey. Vortical Flow Structure around a Cylindrical Bridge Pier: Experimental and Computational Investigation, 3rd Int. Symp. on Shallow Flows, Iowa City, USA, June 4 - 6, 2012. 2012/06/04 00:00:00, . : ,
07/21/2012	19.00	Polydefkis Bouratsis, Panayiotis Diplas, Clinton Dancey, Nikolaos Apsilidis. A Computer Vision Technique for Real-Time Topographic Measurements of Mobile Sediment Beds, 3rd Int. Symp. on Shallow Flows, Iowa City, USA, June 4 - 6, 2012. 2012/06/04 00:00:00, . : ,
07/21/2012	20.00	P. Bouratsis, P. Diplas, C. Dancey, N. Apsilidis. The morphology of an evolving scour hole around a bridge pier, River Flows 2012. 2012/08/05 00:00:00, . : ,
07/21/2012	21.00	N. Apsilidis, A. Khosronejad, F. Sotiropoulos, C. Clinton, P. Diplas. Physical and Numerical Modeling of the Turbulent Flow Field Upstream of a Bridge Pier, ICSE6 Paris - August 27-31, 2012. 2012/08/27 00:00:00, . : ,

<b>TOTAL:</b>	<b>5</b>
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**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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**(d) Manuscripts**

<u>Received</u>	<u>Paper</u>
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03/07/2011	12.00	P. Diplas, C. Dancey, M. Valyrakis, A. Celik, K. Greer. The Role of Turbulence on the Initiation of Sediment Movement, (03 2011)
03/07/2011	13.00	M. valyrakis, P. diplas, C. Dancey. Entrainment of coarse grains in turbulent flows: an Extreme Value Theory approach, (03 2011)
03/07/2011	14.00	M. Valyrakis, P. Diplas, C. Dancey. Prediction of coarse pa rticle movement with adaptive neuro fuzzy inference systems, (03 2011)
03/07/2011	9.00	M. Valyrakis, P. Diplas, C. Dancey. Modelling the impulses causing entrainment of coarse grains by means of Extreme Value Theory, (03 2011)
03/26/2013	27.00	A.O. Celik, P. Diplas, C. Dancey. Instantaneous pressure measurements on aspherical grain under threshold owconditions, Journal of Fluid Mechanics (02 2013)
07/21/2012	17.00	Manousos Valyrakis, Panayiotis Diplas, Clint Dancey. Entrainment of Coarse Particles in Turbulent Flows: An Energy Approach, Journal of Geophysical Research-Earth Surface (01 2012)

**TOTAL: 6**

**Number of Manuscripts:**

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**Books**

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Patents Submitted**

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**Patents Awarded**

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**Awards**

Panos Diplas received the H.A. Einstein Award, ASCE 2012, for significant contributions in the understanding of river mechanics, erosional processes and sediment transport.

Panos Diplas received the K. E. Hilgard Hydraulic Prize, ASCE 2012, for the paper “Turbulent Flow through Idealized Emergent Vegetation,” published in the December 2010 issue of the J. of Hydraulic Engineering, (with T. Stoesser and S.J. Kim of Georgia Tech).

#### Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Nikolaos Apsilidis	0.75	
Pol Bouratsis	0.75	
<b>FTE Equivalent:</b>	<b>1.50</b>	
<b>Total Number:</b>	<b>2</b>	

#### Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

#### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Panos Diplas	0.00	
Clint L. Dancey	0.00	
<b>FTE Equivalent:</b>	<b>0.00</b>	
<b>Total Number:</b>	<b>2</b>	

#### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

#### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: .....	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense .....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: .....	0.00

**Names of Personnel receiving masters degrees**

<u>NAME</u>
<b>Total Number:</b>

**Names of personnel receiving PHDs**

<u>NAME</u>
<b>Total Number:</b>

**Names of other research staff**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

**Sub Contractors (DD882)**

**Inventions (DD882)**

**Scientific Progress**

- Performed bridge scour experiments over a wide range of pier diameter based Reynolds numbers, from 26,000 to near 106. The largest Reynolds number obtained during this study is the highest ever reported in the literature.
- Digital particle image velocimetry measurements revealed the dependence of the vortex structure and associated flow complexity in the vicinity of the pier upon the Reynolds number.
- Non-intrusive three-dimensional photogrammetry methods developed during the course of this project identified three separate phases during the scour hole evolution. Details about erosion rates, excavation volumes and 3D topography were obtained through this newly developed technique. This represents the first successful approach to capture the temporal development of the scour hole continuously from scour initiation to final equilibrium geometry.
- Extensive velocity, channel bed elevation, pier surface pressure and related measurement have been obtained for a wide range of flow, pier diameter and sediment size conditions. These are currently used to validate CFD models.

### **Technology Transfer**